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Computational and Parametric Study of Aerodynamic Coefficients of Fixed-Wing Micro Aerial Vehicles

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***Abstract*—The work carried out in this paper is aimed towards CFD study and empirical determination of parameters that effect the lift and drag coefficients of fixed wing micro aerial vehicles. Empirical formulae are devised for calculating these aerodynamic coefficients in order to alleviate the computational cost incurred by conventional high fidelity software tools. Two of the most widely used planform shapes for fixed wing micro aerial vehicles i.e. rectangular and Zimmerman shapes are chosen for study with cambered low Reynolds number airfoil E61. The results obtained using the empirical formulae are compared with that of ANSYS FLUENT[1] software. Moreover, flat plate results from wind tunnel experimentations by Thomas Mueller et al.[2] have been compared with corresponding FLUENT[1] CFD results as well as with the empirical formulation.**

***Keywords*—Micro Aerial Vehicles (MAV), CFD Fluent[1], Wind Tunnel Test, Lift Coefficient, Drag Coefficient, Advance Ratio, Wetted Area Ratio Introduction**

I. Introduction

The use of micro aerial vehicles (MAVs) or micro-sized Unmanned Aerial Vehicles (UAVs) has gained an increase in interest over the recent times, with the primary objective of carrying out otherwise difficult or expensive surveillance and reconnaissance missions. The trend is to develop micro aerial vehicles with span length of less than 30 cm. What makes a micro aerial vehicle specifically distinct from relatively bigger sized aerial vehicles is the operating low Reynolds number. Typically, they operate in the Reynolds number regime of 10^4-10^5.

In our present study, we developed empirical formulae for capturing the effecting factors. After thorough literature survey, we decided on an appropriate design of experiment model covering the extreme values of these parameters and a central value. FLUENT simulations with unsteady flow model were carried out at these design points for rectangular and Zimmerman planform shapes (with E61[3] airfoil shape) for both propeller mounted as well as propeller un-mounted cases. Each of the propeller un-mounted FLUENT [1] simulations gave result in 3-4 hours and each of the propeller mounted FLUENT [1] simulations gave result in 3-4 days. These highly time consuming results were compared against our empirical models. In order to validate the robustness of our FLUENT [1] setup and simulation conditions, we ran simulations for flat plat cases as well and compared the same against wind tunnel data available from experiments by Mueller et al.[2]

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Nomenclature

C_L	Lift coefficient
C_D	Drag coefficient
C_{D0}	Zero-lift drag coefficient
C_T	Thrust coefficient
V_∞	Free stream velocity
V_i	Induced velocity
V	Net velocity
n	Rotational speed of the propeller
R	Radius of the propeller
S	Wing surface area
S_{wet}	Wetted surface area of the wing
λ	Advance ratio
α	Angle of attack
AR	Aspect ratio
b	Wing span
ρ	Density
A	Propeller frontal area
D	Prop diameter
T	Thrust force
K_P, K_V, K	Mueller constants
ΔC_L	Lift coefficient difference
ΔC_D	Drag coefficient difference
Prop	Propeller
AOA	Angle of attack
Wetted area ratio	S_{wet}/S

II. Empirical Formulation of Lift and Drag Coefficients

The CFD computations of lift and drag coefficients for prop-less case is relatively inexpensive as compared to the propeller mounted case. So, we tried to devise a formula for calculating

ΔC_L and then add the result to prop-less lift coefficient to get the result for prop-mounted case.

$$\Delta C_L = C_L|_{\text{with prop}} - C_L|_{\text{without prop}} \tag{1}$$

Let, V_∞ be the free stream velocity upstream of the propeller. If we assume Froude's momentum theory model [4], then the velocity downstream of the propeller can be assumed to be incremented by 2 * (induced velocity, V_i), where

$$V_i = \frac{-V_\infty + \sqrt{V_\infty^2 + \frac{2T}{\rho A}}}{2}. \tag{2}$$

And the downstream velocity is:

$$V = V_\infty + 2V_i = \sqrt{V_\infty^2 + \frac{2T}{\rho\pi R^2}}. \tag{3}$$

Let us assume that the wetted area of the wing sees a velocity of $(V_\infty + 2V_i)$ and the remaining area of the wing sees a velocity of V_∞. Fig. 1 shows the considered model:

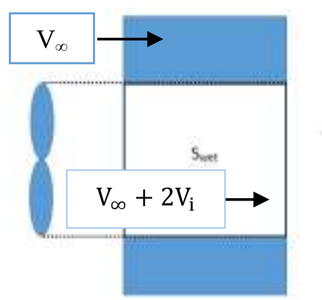

Figure 1: Assumed Flow Model

$$C_L|_{\text{with prop}} = \frac{\frac{1}{2}\left[\rho\left(\left(V_\infty^2 + \frac{2T}{\rho\pi R^2}\right)S_{wet} + V_\infty^2(S - S_{wet})\right)C_L|_{\text{without prop}}\right]}{\frac{1}{2}\rho V_\infty^2 S} \tag{4}$$

$$\Delta C_L = \left(\frac{2T}{\rho\pi R^2 V_\infty^2}\right)\left(\frac{S_{wet}}{S}\right) C_L|_{\text{without prop}} \tag{5}$$

$$\Delta C_L = (\text{constant2})\left(\frac{C_T}{\lambda^2}\right)\left(\frac{S_{wet}}{S}\right) C_L|_{\text{without prop}} \tag{6}$$

n denotes the propeller rotational speed, D denotes the propeller diameter, C_T denotes the thrust coefficient and λ denotes advance ratio, (S_{wet}/S) is the wetted area ratio.We know that C_T is a function of λ. So, if we assume $C_T = f_1(\lambda)$ and $f_2(\lambda) = f_1(\lambda)/\lambda^2$,

$$\Delta C_L = (\text{constant2}) f_2(\lambda)\left(\frac{S_{wet}}{S}\right) C_L|_{\text{without prop}} \tag{7}$$

Thus, we ΔC_L depends on the following parameters:

- λ, advance ratio
- Wetted area ratio, $\left(\frac{S_{wet}}{S}\right)$
- Lift coefficient without propeller
- $C_L|_{\text{without prop}}$

Proceeding in the same manner as above,

$$\Delta C_D = (\text{constant2}) f_2(\lambda)\left(\frac{S_{wet}}{S}\right)(C_{D0} + kC_L^2) \tag{8}$$

Where, C_{D0} is the zero lift drag coefficient part and kC_L^2 is the induced drag coefficient part of the prop-less MAV configuration. C_{D0} is usually constant equal to .015[5]. The value of k [5] again depends on aspect ratio and planform shape of the micro aerial vehicle. Therefore, we see that ΔC_D depends on the following parameters:

- Advance ratio, λ
- Wetted area ratio, $\left(\frac{S_{wet}}{S}\right)$
- The factor kC_L^2

III. Design of Experiment and CFD Simulations

A literature survey has been done in order to decide the typical operating range of coefficient of thrust (C_T) and wetted area ratio, $\left(\frac{S_{wet}}{S}\right)$ for MAVs. Points A, B, C, D and E shown in Fig. 2 below constitute our design of experiment.

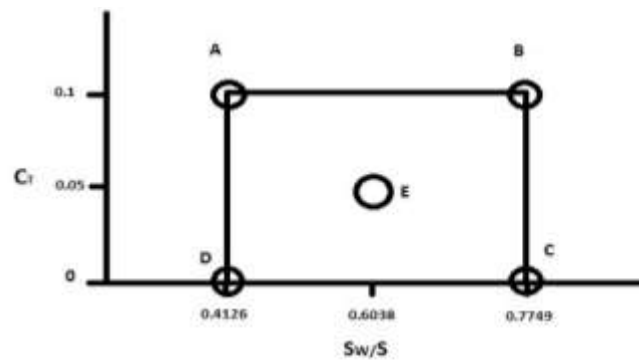

Figure 2: Design Points for Simulation

Two of the most widely used planform shapes viz. Zimmerman and Rectangular with low Reynolds Number airfoil E61 are chosen for CFD analysis at the designated points. Fig. 3 below shows a set of generated wing models:

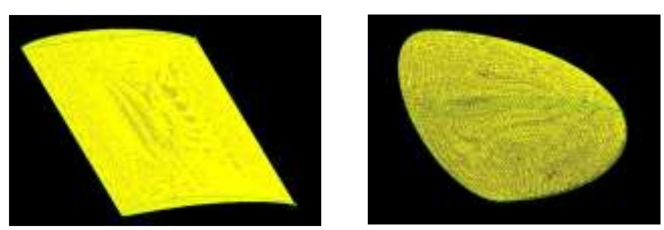

Figure 3: Rectangular and Zimmerman Planform with E61 Airfoil

A. *Design Point A*

V_∞ = 6.326 m/s | RPM = 8000 | Aspect Ratio = 2 | Propeller Diameter = 6 inch | NAL MAV PR01 Propeller.
Table 1 below shows the dimensions for point A:

Dimension for Zimmerman Wing AR=2

Semi-major axis of Elliptical one	a3=230.9090909 mm
Semi-minor axis of Elliptical one	a1=73.53792704 mm
Semi-major axis of Elliptical two	a2=220.6137811 mm
Semi-minor axis of Elliptical two	a3= 230.9090909 mm
Planform Area	S=0.1067 m^2
Root Chord length	C=294.1517082 mm

Dimension for Rectangular Wing AR=2	
Span of the Wing	b=369.3448853 mm
Chord of the Wing	c=184.6724427 mm
Planform Area	S=0.06821 m^2

Table 1: Wing Dimensions

Table 2 shows the result generated using FLUENT [1]:

C_T=0.1	Zimmerman Wing		Rectangular Wing		Prop-Zimmerman		Prop-Rectangular	
AOA	CL	CD	CL	CD	CL	CD	CL	CD
0	0.26	0.03	0.32	0.05	0.44	0.12	0.62	0.16
10	0.67	0.11	0.78	0.14	0.95	0.23	1.18	0.3
20	1.00	0.31	0.94	0.31	1.35	0.49	1.61	0.59
30	0.99	0.57	0.86	0.49	1.58	0.87	1.8	0.98
35	0.88	0.61	0.79	0.56	1.59	1.08	1.79	1.19
40	0.87	0.73	0.74	0.62	1.55	1.28	1.72	1.41

Zimmerman Wing		Rectangular Wing		Difference in Δ	
ΔCL	ΔCD	ΔCL	ΔCD	δ(ΔCL)	δ(ΔCD)
0.18	0.09	0.3	0.11	0.12	0.02
0.28	0.12	0.4	0.16	0.12	0.04
0.35	0.18	0.67	0.28	0.32	0.1
0.59	0.3	0.94	0.49	0.35	0.19
0.71	0.47	1.00	0.63	0.29	0.16
0.68	0.55	0.98	0.79	0.3	0.24

Table 2: CFD Simulation for Point A

B. *Design Point B*

V_∞ = 6.326 m/s | RPM = 8000 | Aspect Ratio = 2 | Propeller Diameter = 6 inch | NAL MAV PR01 Propeller.
Table 3 below shows the dimensions for point B:

Dimension for Zimmerman Wing AR=2	
Semi-major axis of Elliptical one	a3=115.4545455 mm
Semi-minor axis of Elliptical one	a1=36.76896352 mm
Semi-major axis of Elliptical two	a2=110.3068906 mm
Semi-minor axis of Elliptical two	a3= 115.4545455 mm
Planform Area	S=0.026678 m^2
Root Chord length	C=0.1471 m

Dimension for Rectangular Wing AR=2	
Span of the Wing	b=196.6606685 mm
Chord of the Wing	c=98.33033425 mm
Planform Area	S=0.0193377 m^2

Table 3: Wing Dimensions

Table 4 shows the result generated using FLUENT [1]:

CT=0.1	Zimmerman Wing		Rectangular Wing		Prop-Zimmerman		Prop-Rectangular	
AOA	CL	CD	CL	CD	CL	CD	CL	CD
0	0.26	0.04	0.29	0.05	0.65	0.18	0.83	0.21
10	0.68	0.12	0.76	0.15	1.26	0.33	1.53	0.41
20	0.97	0.29	0.89	0.29	1.77	0.67	2.08	0.8
30	0.97	0.56	0.87	0.51	2.12	1.18	2.42	1.37
40	0.85	0.71	0.8	0.67	2.2	1.82	2.46	2.04

Zimmerman Wing		Rectangular Wing		Difference in Δ	
ΔCL	ΔCD	ΔCL	ΔCD	δ(ΔCL)	δ(ΔCD)
0.39	0.14	0.54	0.16	0.15	0.02
0.58	0.21	0.77	0.26	0.19	0.05
0.8	0.38	1.19	0.51	0.39	0.13
1.15	0.62	1.55	0.86	0.4	0.24
1.35	1.11	1.66	1.37	0.31	0.26

Table 4: CFD Simulation for Point B

C. *Design Point C*

V_∞ = 19 m/s | RPM = 8000 | Aspect Ratio = 2 | Propeller Diameter = 6 inch | NAL MAV PR01 Propeller.
Table 5 below shows the dimensions for point C:

Dimension for Zimmerman Wing AR=2	
Semi-major axis of Elliptical one	a3=115.4545455 mm
Semi-minor axis of Elliptical one	a1=36.76896352 mm
Semi-major axis of Elliptical two	a2=110.3068906 mm
Semi-minor axis of Elliptical two	a3= 115.4545455 mm
Planform Area	S=0.026678 m^2
Root Chord length	C=0.1471 m
Dimension for Rectangular Wing AR=2	
Span of the Wing	b=196.6606685 mm
Chord of the Wing	c=98.33033425 mm
Planform Area	S=0.0193377 m^2

Table 5: Wing Dimensions

Table 6 shows the result generated using FLUENT [1]:

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C_T=0	Zimmerman Wing		Rectangular Wing		Prop-Zimmerman		Prop-Rectangular	
AOA	CL	CD	CL	CD	CL	CD	CL	CD
0	0.319	0.039	0.399	0.052	0.319	0.049	0.397	0.063
10	0.723	0.124	0.836	0.155	0.733	0.137	0.833	0.166
20	1.048	0.303	1.121	0.333	1.091	0.334	1.188	0.374
30	0.999	0.567	0.899	0.507	1.3	0.68	1.33	0.706
40	0.844	0.708	0.791	0.662	1.23	1.01	1.23	1.02

Zimmerman Wing		Rectangular Wing		Difference in Δ	
ΔCL	ΔCD	ΔCL	ΔCD	δ(ΔCL)	δ(ΔCD)
0	0.01	0.002	0.011	0.002	0.001
0.01	0.013	0.003	0.011	0.007	0.002
0.043	0.031	0.067	0.041	0.024	0.01
0.301	0.113	0.431	0.199	0.13	0.086
0.386	0.302	0.439	0.358	0.053	0.056

Table 6: CFD Simulation for Point C

D. Design Point D

V_∞ = 19 m/s | RPM = 8000 | Aspect Ratio = 2 | Propeller Diameter = 6 inch | NAL MAV PR01 Propeller.
Table 7 below shows the dimensions for point D:

Dimension for Zimmerman Wing AR=2	
Semi-major axis of Elliptical one	a3=230.9090909 mm
Semi-minor axis of Elliptical one	a1=73.53792704 mm
Semi-major axis of Elliptical two	a2=220.6137811 mm
Semi-minor axis of Elliptical two	a3= 230.9090909 mm
Planform Area	S=0.1067 m^2
Root Chord length	C=294.1517082 mm
Dimension for Rectangular Wing AR=2	
Span of the Wing	b=369.3448853 mm
Chord of the Wing	c=184.6724427 mm
Planform Area	S=0.06821 m^2

Table 7: Wing Dimensions

Table 8 shows the result generated using FLUENT [1]:

C_T=0	Zimmerman Wing		Rectangular Wing		Prop-Zimmerman		Prop-Rectangular	
AOA	CL	CD	CL	CD	CL	CD	CL	CD
0	0.309	0.032	0.429	0.05	0.308	0.045	0.423	0.062
10	0.703	0.114	0.868	0.156	0.722	0.129	0.864	0.167
20	1.03	0.3	1.149	0.337	1.073	0.327	1.21	0.371
30	0.989	0.559	0.874	0.493	1.232	0.658	1.27	0.669
40	0.838	0.701	0.785	0.658	1.136	0.937	1.133	0.929

Zimmerman Wing		Rectangular Wing		Difference in Δ	
ΔCL	ΔCD	ΔCL	ΔCD	δ(ΔCL)	δ(ΔCD)
0.001	0.013	0.006	0.012	0.005	0.001
0.019	0.015	0.004	0.011	0.015	0.004
0.043	0.027	0.061	0.034	0.018	0.007
0.243	0.099	0.396	0.176	0.153	0.077
0.298	0.236	0.348	0.271	0.05	0.035

Table 8: CFD Simulation for Point D

E. Design Point E

V_∞ = 14 m/s | RPM = 8000 | Aspect Ratio = 2 | Propeller Diameter = 6 inch | NAL MAV PR01 Propeller.
Table 9 below shows the dimensions for point E:

Dimension for Zimmerman Wing AR=2	
Semi-major axis of Elliptical one	a3=153.9393939 mm
Semi-minor axis of Elliptical one	a1=49.02528469 mm
Semi-major axis of Elliptical two	a2=147.0758541 mm
Semi-minor axis of Elliptical two	a3=153.9393939 mm
Planform Area	S=0.047395 m^2
Root Chord length	C=0.196101 m

Dimension for Rectangular Wing AR=2	
Span of the Wing	b=252.4092181 mm
Chord of the Wing	c=126.204609 mm
Planform Area	S=0.03185521 m^2

Table 9: Wing Dimensions

Table 10 shows the result generated using FLUENT [1]:

C_T=0.05	Zimmerman Wing		Rectangular Wing		Prop-Zimmerman		Prop-Rectangular	
AOA	CL	CD	CL	CD	CL	CD	CL	CD
0	0.331	0.043	0.392	0.053	0.367	0.066	0.437	0.076
10	0.739	0.13	0.83	0.156	0.808	0.163	0.908	0.189
20	1.072	0.308	1.13	0.336	1.179	0.374	1.277	0.414
30	0.989	0.554	0.884	0.496	1.376	0.702	1.465	0.772
40	0.885	0.741	0.781	0.654	1.318	1.078	1.375	1.113

Zimmerman Wing		Rectangular Wing		Difference in Δ	
ΔCL	ΔCD	ΔCL	ΔCD	δ(ΔCL)	δ(ΔCD)
0.036	0.023	0.045	0.023	0.009	0
0.069	0.033	0.078	0.033	0.009	0
0.107	0.066	0.147	0.078	0.04	0.012
0.387	0.148	0.581	0.276	0.194	0.128
0.433	0.337	0.594	0.459	0.161	0.122

Table 10: CFD Simulation for Point E

IV. Comparison and Robustness of the CFD Setup

In order to check the validity of our simulation setup and robustness of our empirical simulation, we did analysis of a flat plate Zimmerman wing with propeller diameter of 6 inches, free stream velocity of 5.031 m/s, Reynolds Number of 70000, RPM of 8000, aspect ratio of 2, span length of 0.319024 m and root chord of .2032 m. Fig. 4 shows the lift coefficient comparison between propeller-mounted numerical and empirical cases :

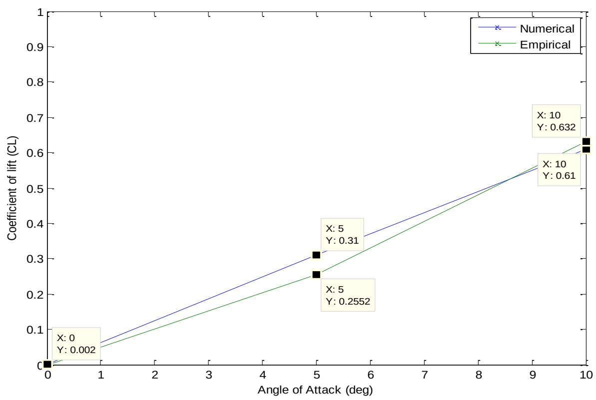

Figure 4: Lift Coefficient Comparison

Fig. 5 shows the drag coefficient comparison between propeller-mounted numerical and empirical cases:

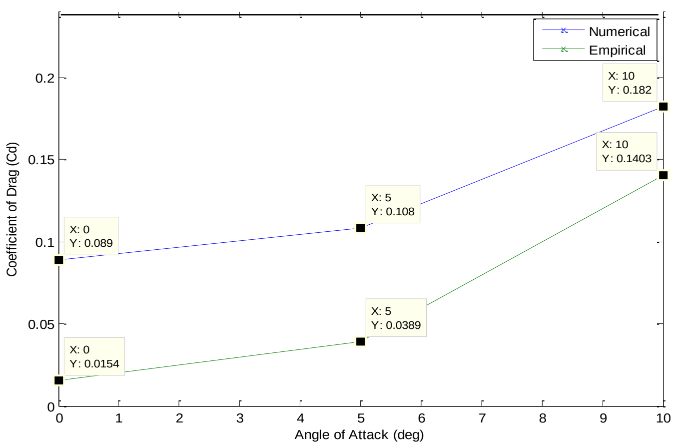

Figure 5: Drag Coefficient Comparison

V. Summary

A proper literature survey was carried out to understand the aerodynamics of micro aerial vehicles. We have tried to work out the factors effecting the lift and drag coefficients when propeller is mounted. CFD simulations have been run to generate the values of these aerodynamic coefficients and the same has been compared against mathematical models. CFD results for flat plat agree quite well with the experimental flat plate values suggested by Mueller [5]. Mathematically developed formulations seem to support the propeller mounted lift coefficient but not the drag coefficient very well thereby indicating scope for improvement. However the mathematical models can't predict the aerodynamic coefficient at higher angle of attack whereas the CFD simulation results obtained for over a wide operating range of MAVs can be used to predict the aerodynamic value even at substantial angle of attack. Since the results depend on Coefficient of Thrust and S_{wet}/S ratio it is applicable to any MAVs propeller within the design operating range.

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About Author (s):

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